

Design of a High-Throughput Plasma-Processing System

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ABSTRACT

Sandia National Laboratories has demonstrated significant performance gains in crystalline silicon solar cell technology through the use of plasma-processing for the deposition of silicon nitride by Plasma Enhanced Chemical Vapor Deposition (PECVD), plasma-hydrogenation of the nitride layer, and reactive-ion etching of the silicon surface prior to the deposition to decrease the reflectivity of the surface. One of the major problems of implementing plasma processing into a cell production line is the batch configuration and/or low throughput of the systems currently available. This report describes the concept of a new in-line plasma processing system that could meet the industrial requirements for a high-throughput and cost effective solution for mass production of solar cells.

INTRODUCTION

GT Solar Technologies, Inc. is a manufacturer and supplier of equipment and turnkey fabrication lines for manufacturing photovoltaic multi-crystalline wafers and solar cells. Internationally recognized for its experience and knowledge of the photovoltaic business, including wafer and cell processing, the company maintains a high level of entrepreneurial spirit with a fast response capability to serve the rapidly growing photovoltaic industry.

GT Solar recognizes that reliability and low cost of manufacturing are keys to the continued growth of the PV industry. Therefore, GT Solar has identified certain wafer and cell processing steps that with further development will result in higher efficiency and lower cost. One of these steps is the deposition of silicon nitride by Plasma Enhanced Chemical Vapor Deposition (PECVD). Silicon nitride has an advantage in the cell process in that it provides an antireflective coating and a means to passivate the cell in one operation. As part of its development effort, GT Solar has entered into a contract with Sandia National Laboratories to provide this preliminary conceptual design and cost estimate of a high-throughput PECVD system. GT Solar has placed a special emphasis on cost-savings in the solar cell production process.

PECVD and hydrogenation processes for solar cells have historically been done in batch systems using tube-type or parallel plate reactors. In a tube-type reactor, wafers are typically loaded into a carrier made of parallel graphite plates. After the carrier is inserted into a furnace tube and connected to a RF power supply, the tube is evacuated and the temperature and gas flows are stabilized. The RF power provides the energy to allow deposition of silicon nitride films at low temperature, typically around 350 C. The actual deposition process is only a few

minutes long, but the time required for pressure and temperature stabilization limits the total cycle time to about 30 minutes. A typical PECVD furnace such as the Pacific Western Coyote will have two tubes and a batch size of 140 wafers in each tube (100 mm x 100 mm) to achieve a maximum throughput of approximately 560 wafers per hour. Although they have a relatively high throughput in a small footprint, the carrier design has made it difficult to automate the loading operation. An operator is required to load and unload the carriers.

In a parallel plate reactor, the wafers are loaded onto a flat carrier plate that is inserted into a vacuum chamber. These systems can achieve higher throughput with the use of vacuum load locks that isolate the process chamber(s) from atmosphere. A high throughput system might require a batch size of 100 wafers, requiring a carrier plate approximately 1 square meter in size. The systems can be quite large and expensive as compared to the tube-type reactors, especially if automatic wafer and carrier handling is included.

TASK 1 - In-Line High Throughput PECVD System

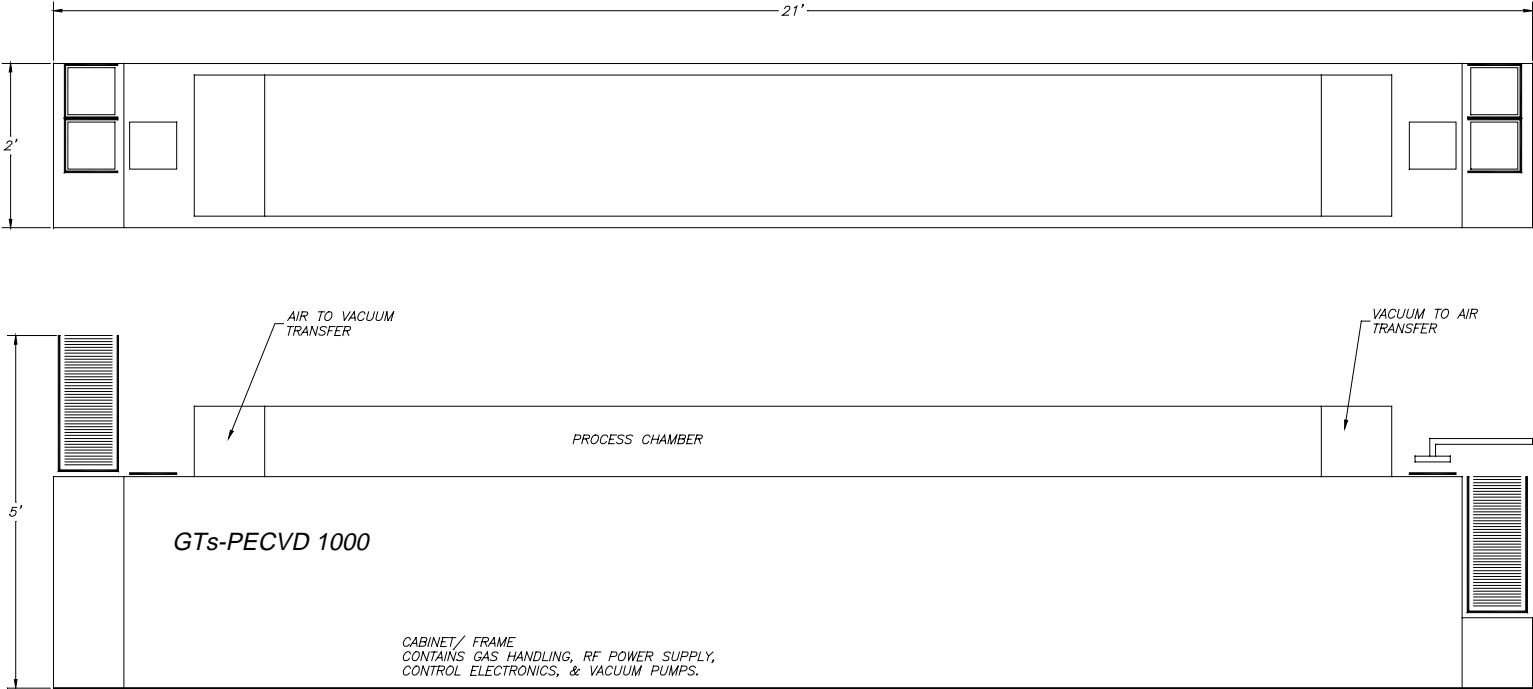
The goal of this task is to conduct an engineering study to develop a conceptual design for equipment that will deposit silicon-nitride on silicon wafers with a refractive index between 2.0 and 2.4. In support of its work, GT Solar has interviewed and consulted with solar cell manufacturers and equipment suppliers concerning the process, equipment throughput, and budgetary cost criteria. A high level of interest was shown by these manufacturers in having a high throughput automated PECVD system that could easily be added to a cell production line.

Conceptual Design

The conceptual design shown in Figure 1 takes into consideration the following requirements: Automatic loading and unloading of the wafers, belt operated system, processing speed to meet the throughput requirements of 1000 wafers/hr, and the process for achieving the deposition parameters. The figure shows that the system will include the following sub-systems:

- a. Loading and unloading wafer transfer system
- b. Belt transfer mechanism
- c. Load locks
- d. Vacuum chamber
- e. Gas handling components
- f. RF power supply and controls
- g. Vacuum pumps

FIGURE 1 In-Line PECVD System, the GTs-PECVD 1000



Wafer Throughput Calculations

The consensus of the potential customers and industry participants is that GT Solar should consider the design of a machine with a minimum throughput of 1000 wafers/hr. Such throughput may be achieved according to the following calculations.

Based on 1000, 5" wafers per hour (single row on the belt @ 5.2" center to center), equals 16.7 wafers per minute, which is equivalent to a belt speed of 87"/min.

The current range of deposition rate for silicon nitride in a parallel plate reactor is in the range of 200 to 600 Å/min. Assuming a rate of 400 Å/min, and a required deposition thickness of 800 Å, a 2 min deposition is required. A deposition zone approximately 15 feet long is required.

Capital Cost Estimates

Materials -

Chamber

- Belt drives
- Load Locks
- Gas Handling
- Vacuum Equipment
- Wafer Handling
- Electronics
- Controls
- Computer Hardware

Labor and Overhead -

- Engineering
- Manufacturing
- Software

Other Expenses -

- G&A
- 7% Fee

Total	<hr/> \$ 947,000
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Operational Cost Estimate

A deposition area 15 feet long and 8 inches wide is 1440 sq. inches. A typical batch (tube type) PECVD system occupies a deposition area of 2400 sq. inches (for 96, 5" wafers). Therefore, assuming a similar diode geometry is maintained, the RF power requirements for an in-line system will be approximately 60% of that required for a batch system. A 1500-watt RF power supply should be sufficient. The power needed to heat 1000 wafers per hour to 350 degree C is approximately 10 kW. This is a combination of IR and resistance heaters. In

addition to another 5 kW for controls and pumps, we estimate the total power requirement is about 17 kW. At \$0.10/kwhr, the power cost will be \$1.70/hour.

We assume the usage rates of process gases are similar to the current batch processes, where each wafer requires approximately 17cc of silane and 140 cc of ammonia. At 1000 w/hr, the system uses 17 l/hr of silane and 140 l/hr of ammonia. At \$0.75/l for silane and \$0.006/l for ammonia, the total process gas cost is \$13.60/hr.

The total operational cost is $\$1.70 + \$13.60 = \$15.30/\text{hr}$ or approximately 1.5 cents per 5" wafer. We compared this to the TiO_2 APCVD process and found it also costs about 1.5 cents per 5" wafer, but does not provide any cell passivation. At 2.2 watts per cell, the cost per watt for PECVD is 0.7 cents.

TASK 2 - PLASMA HYDROGENATION

The deposition area is divided into multiple gas zones to allow changing the film index of refraction and hydrogen content. The incremental cost of adding each gas zone is approximately \$20K including plumbing and controls for silane, ammonia, and nitrogen. We expect a total of two zones will be required for the optimized silicon nitride process with hydrogenation.

TASK 3 - REACTIVE ION ETCHING

The processing of self-aligned, selective emitter solar cells requires a reactive ion etch of the emitter prior to deposition of silicon nitride [1]. In this process, the printed cells were etched for about 1 minute in 100 mTorr of SF_6 prior to the PECVD deposition of silicon nitride. In this task we have considered the design modifications required to add the RIE process prior to the PECVD process in the proposed in-line plasma processing system.

Assuming the same throughput of 1000 5" wafers per hour, a one-minute RIE process will require about 87" of plasma exposure. The process chamber will be extended by about 8'. The RIE requires a pressure between 100 and 200 mTorr, whereas the PECVD pressure is about 2 Torr. It is likely that a third load-lock will be required between the two chambers.

The cost to add the RIE process to the proposed in-line system is estimated to be \$215,000, and will include the following components:

- a) Process chamber with belt mechanism
- b) RF power supply
- c) Vacuum system
- d) Gas handling system
- e) Load-lock chamber
- f) Engineering & overhead

We believe the addition of RIE to the system is feasible as long as the process time is limited to one to two minutes and the belt speed and/or chamber length is adjusted accordingly.

CONCLUSION

A payback analysis was performed to see if an existing solar cell manufacturer currently using an APCVD TiO₂ AR coating could justify the purchase of an in-line PECVD system. Our calculations show that if the system cost is \$950K, and the cell efficiency is improved by 7% (for example from 2.1 watts with TiO₂ to 2.25 watts per 5" cell with nitride), the payback for a 12 MW factory would be less than one year. Of course improvements in cell efficiency will depend on many factors, such as the cell process and the quality of the starting wafers.

ACKNOWLEDGMENTS

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REFERENCES

1. D. S. Ruby, P. Yang, and S. Narayanan, "Recent Progress on the Self-Aligned, Selective-Emitter Silicon Solar Cell", Proc. 26th IEEE PVSC, September 1997, pp. 39-42